Manned Flight Simulator and the Impact on Navy Weapons Systems Acquisition.

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ABSTRACT

The dramatic rise in the level of complexity and the cost of modern airborne weapons systems has overwhelmed the ability for conventional flight test techniques to evaluate system performance and specification compliance. The U.S. Navy has developed a unique, modern pilot-in-the-loop simulation facility targeted at reducing the development cost and shortening the time-line required for new aircraft systems. The Manned Flight Simulator facility, located at the Naval Air Warfare Center - Aircraft Division, provides a flexible simulation capability through the use of modular hardware and software designs that can handle almost all simulations required for Test and Evaluation and Training. This paper will survey technical capabilities, discuss applications to current major Navy projects and demonstrate how modularity and extensive use of shared assets reduce program costs, increases safety, and optimizes flight test. In addition, specific examples of technology transfer from the MFS to other government agencies and private industry will be explored.

LIST OF ABBREVIATIONS

DIS	Distributed Interactive Simulation
COTS	Commercial Off-The-Shelf
NAWC-AD	U.S. Navy's Naval Air Warfare Center - Aircraft Division
ACETEF	Air Combat Test and Evaluation Facility
T&E	Test and Evaluation
MFS	Manned Flight Simulator Facility
IOS	Instructor-Operator Station
IG	Image Generator

PROBLEM STATEMENT

The past decade has seen explosive growth in the complexity and cost of modern weapons systems. This presents a challenge for Test and Evaluation organizations, as the time allowed to test aircraft systems and sub-systems have not been expanding in a proportional fashion. Figure 1.0 shows this trend. Thus, T&E organizations have been forced to develop new methods for extensively testing new weapons systems yet remain within project time requirements.

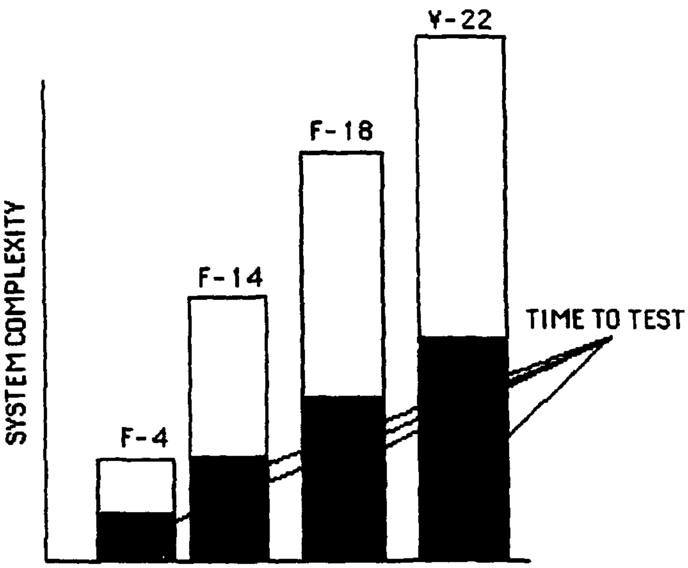


Figure 1.0

NAWC-AD, formerly the Naval Air Test Center, has developed the Manned Flight Simulator Facility to meet this challenge.

MANNED FLIGHT SIMULATOR OVERVIEW

The MFS is a single laboratory located in the Air Combat Test and Evaluation Facility (ACETEF).

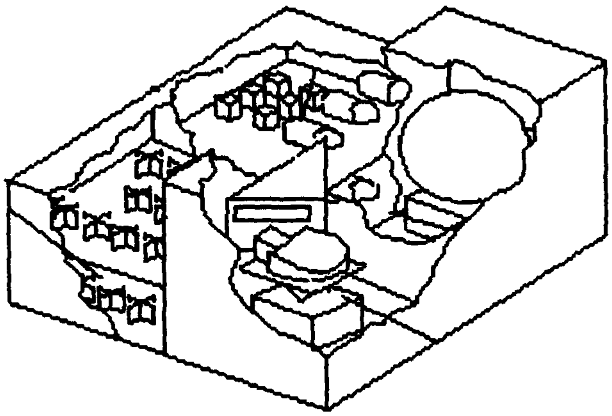
TO WHOM IT MAY CONCERN:

Here is a copy of Professional Papers written by various people here at the Naval Air Warfare Center Aircraft Division. It was requested that a copy of each of the professional papers be sent to DTIC for retention.

If you have any questions, please contact Dorothy Reppel, 326-1709 or (301) 826-1709.

P.S. All the enclosed papers have been cleared for public release.

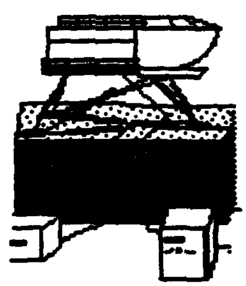
(Figure 2) The unique aspect of the MFS resides in the design of the simulation cockpits and interfaces at each of the facility simulation stations.



MFS FACILITY
Figure 2.0

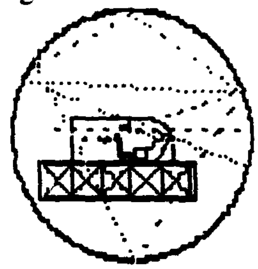
The MFS contains five simulation stations: a single 40 foot dome, a six degree of freedom motion base, and three engineering development stations. The facility has a central computer facility that contains a large variety of host computers and visual image generators. The central computer cluster includes Vax 6440's, Model 4000-90's, Silicon Graphics Onyx Racks with multiple reality engines and video output cards, ADI AD10's and AD100's and many other systems. For visual image generation the facility shares among the simulation stations a Compuscence IV, a Compuscence IVA and several ESIG-2000s. MFS is expecting delivery of a PT2000 in the near future. All of the IG'S output can be switched from one simulation station to the next as required with an in-house designed and constructed electronic video switcher.

The motion platform station features a Rediffusion motion base and Wide II infinity optical system that has a 200x45 degree field of view. The light-tight box has been modified to accept roll-in, roll-out cockpits.



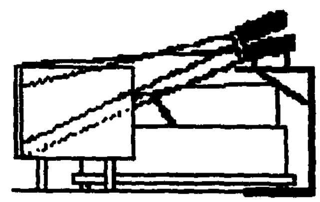
The motion station is capable of producing ±1.5G vertical ±0.7G lateral & longitudinal acceleration, 38.5° to +32° pitch with ±27.5° roll and ±36° yaw with ± 250 dpss angular acceleration. This station is primarily used for rotary wing applications and for the landing phase of fixed wing craft.

The forty foot dome has 360° x 290° low resolution background image with a 60° x 80° high resolution forward looking fixed insert.



The dome has two target projector pairs. It is used primarily where a large field of view and tactical maneuvering is required. Modular cockpit access is through large doors located at the second story entryway.

The three engineering development stations are used to support flight test and to develop and validate software development prior to production release of software.



The stations have a 165x40 display screen placed in front of the cockpits, and the screens are front illuminated from projectors mounted on overhead racks. One of the MFS lab stations is dedicated to a helmet mounted display system.

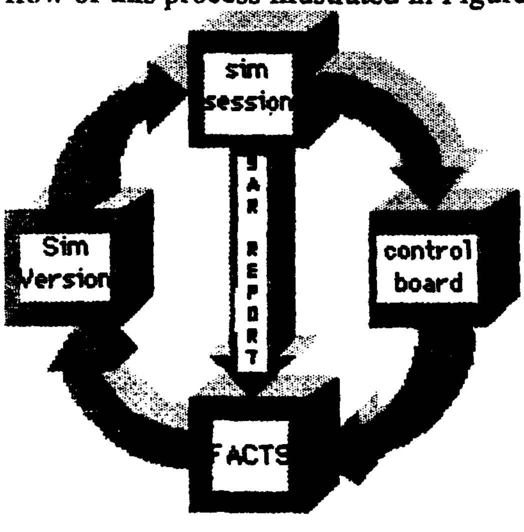
All of the MFS simulation stations are capable of running with actual aircraft flight hardware in the loop. Aircraft flight control and mission computers are located in the central resources cluster, and can be switched to the required simulation station as the cockpit modules move about. This capability is used extensively to validate avionics and flight control systems models, as well as perform testing on the aircraft equipment and software loads themselves.

STANDARD SIMULATION SOFTWARE

The MFS uses high fidelity, non-linear airframe models for its engineering support of T&E. Teams of engineers are assigned to each airframe with the charter to constantly update and improve the fidelity of these models, gathering data from any available source, and using advanced numerical techniques, such as Parameter Identification to update them. The wide range of simulations and software processes that the MFS has been required to simulate long ago highlighted the requirement for the facility to have a standard set of simulation executive software, easy to use and maintain, and applicable to all six-degree of freedom simulations. The Controls Analysis and Test Loop Environment (CASTLE) software executive was developed to meet this requirement. The system offers user interface windows, equations of motion linear model extraction and parameter identification tools that work with any installed air vehicle simulation. To install a simulation in the MFS, the developer of the simulation provides the aerodynamic, engine and control system models, and plugs them into the shell software. The simulation can also be developed locally from flight test or wind tunnel data.

SOFTWARE DEVELOPMENT PROCESS

The MFS has set into place an extensive system for software discrepancy tracking and resolution. Called "FACTS" for Facility Anomaly Control and Tracking System, this system has allowed the MFS to retain tight control over the configurations of each simulation being used in the laboratory. The menu driven FACTS database is accessible at each engineers workstation over the facility network, and each engineer can review in real-time the status of work requests, discrepancy correction, etc. Each simulation is assigned version numbers that can be used to determine what changes have been made in the code since the previous version. The flow of this process illustrated in Figure 3.0.



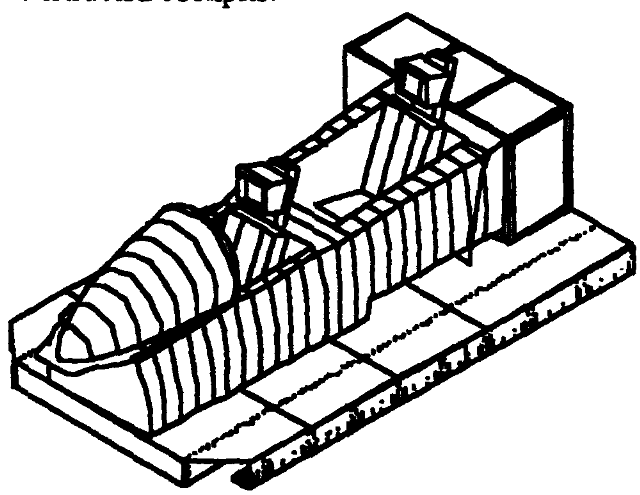
FACTS Flowchart
Figure 3.0

Simulation users generated System Anomaly Reports (SARs) during a lab session. These are entered into the FACTS database, and assigned to be corrected to an engineer or engineering team under the control of the configuration control leader. The work progress is also entered into the FACTS database to interested parties to track progress. When the problem is resolved, the simulation version number is updated to show that changes have been made, and the process begins again.

SIMULATION COCKPIT MODULES

Each simulation cockpit is of a Roll-In, Roll-Out (RIRO) design. The current "stable" of aircraft cockpits include the F-14, V-22, F-18A, F-18F, and AH-1W aircraft. The MFS also has a generic cockpit that can accommodate the grips and throttle clusters from any Navy or Marine aircraft. The cockpits all share a standard footprint base frame that includes mechanical interfaces for the motion base, and a common set of interface hardware to connect to the center host computer cluster.

This gives the MFS a powerful simulation capability in that whenever a new simulation is required, the cockpit can be constructed without requiring any simulation station to be disrupted. Typically, any facility installing a new simulation in an existing asset, be it a dome or motion base, would require months and perhaps years of down time to install and integrate the new simulation asset. At the MFS the new simulation software and the cockpit can be developed during use of the lab by other users, and integration of the new simulation capability, hardware and software, is not disruptive to the lab. The F/A-18F cockpit is shown in Figure 4.0. This example is typical of all the MFS designed and constructed cockpits.



F/A-18F Cockpit Module
Figure 4.0

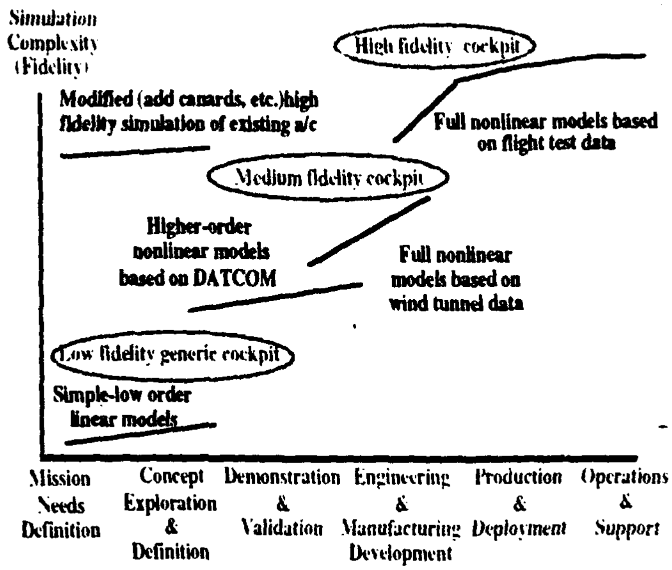
The F/A-18F cockpit was taken from an F/A-18B aircraft that was stricken from the Naval Register. The cockpit is equipped with 5 CTR type displays in both crew stations of a new design for this type aircraft. The use of actual aircraft equipment in the MFS is desired, but in the case of new and developing aircraft this may not always be practical. The cockpit uses high fidelity simulated equipment that has the same form fit and function as the actual aircraft equipment. An actual aircraft mission computer operating over 1553 buses drives these displays. The cockpit was designed to be able to use actual aircraft displays in a "pull-out plug-in" manner when they become available. The MFS standard VME-based interface is employed in the cockpit. The cockpit is motion capable for use in the MFS motion station, and contains digital electric control loaders to replicate the aircraft's force/feel to the pilot.

ACQUISITION SUPPORT - CONCEPT

The need for an MFS-type facility became apparent in the Navy during the EMD of the F-18 aircraft program. The size and complexity of the weapon system installed on that aircraft was a large step beyond any such system that the then-NATC had been asked to evaluate. To test out all possible configurations and malfunctions of the weapons system would have required years of testing, and still many test points would have been prohibited due to the high risk associated with various failure modes.

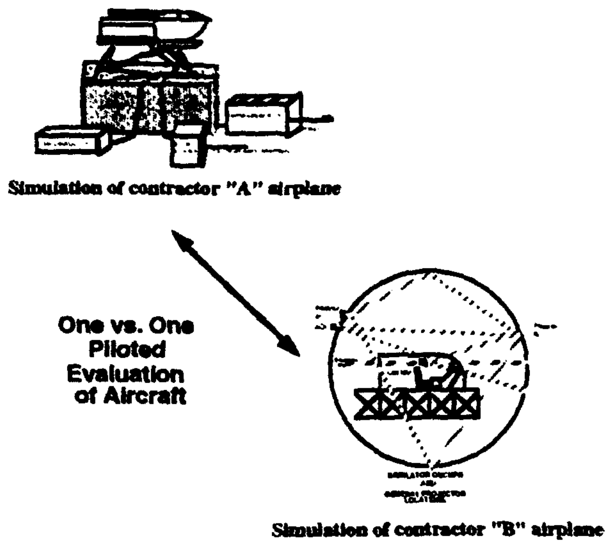
Application of Advanced Simulation and Analysis Capabilities are made to the Research, Development and Acquisition Process from Mission Needs Definition to Operations and Support. The concept of the availability of simulation during the Acquisition Process is shown in figure 5.

As shown, during the early part of the acquisition cycle high fidelity simulations of a specific vehicles/weapon systems are not available and simple lower order models and generic higher order models are used for analytical studies, design, mission analysis and performance predictions. As the development process proceeds and design goals and requirements are better defined, increasingly complex models and simulations become available to support the detailed design, development and testing process.



Simulation Availability and Growth During the Acquisition Cycle
Figure 5

At the beginning phases of the Acquisition Process, many applications of the MFS can be used to enhance the Navy's ability to participate in the development of a weapon system. During the Mission Needs Definition and Concept Exploration & Development phases, the utilization of the MFS in conjunction with ACETEF provides the pilot interface and computational resources to perform basic research and assess the needs of specific Navy missions requirements. For example, the MFS can be used to determine the operational requirements in a combat environment, determine the effects of aircraft aerodynamic configuration on operational capabilities and evaluate analysis methods for high angle of attack super maneuverability. Another example, would be to determine the effectiveness of a weapon system against current and projected threats. During Demonstration and Validation, the MFS provides the capability to do a Fly-off between two competitive aircraft configurations. During this Fly-off, an analytical evaluation and comparison of performance, stability and control, carrier suitability and weapons capabilities can be made to assess the two designs. This evaluation would include pilot evaluations of the two aircraft configurations to asses flying qualities, work load and weapon system effectiveness. A specific example of this would be to conduct piloted simulation carrier approaches and arrestments to evaluate of the carrier suitability of two or more competitive aircraft designs. This process is illustrated in figure 6.



Utilization of MFS Motion Base and Dome for Evaluating Competing Designs
Figure 6

As the weapon system design completes Demonstration and Validation and the program enters into the Engineering Manufacturing and Development Phase, the MFS has an even bigger impact on system development and testing. Utilization of the MFS can be made to support aircraft development by enhancing the Navy's ability to follow and evaluate contractors designs. For example, in flight testing the Navy uses piloted simulation to plan flights, optimize flight profiles and practice high risk maneuvers and emergency procedures. The simulation is used as an analysis tool to understand complex systems such as FCS, make design trade-offs, and provides for efficient use of flight test time and assets.

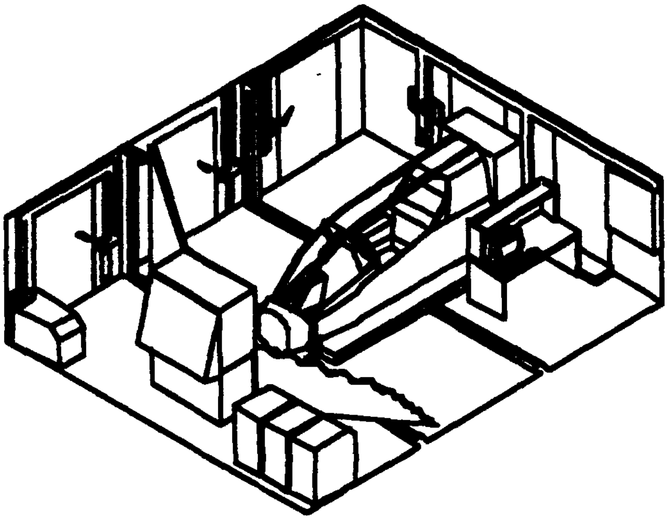
During the Production and Deployment and Operations and Support, the MFS provides for timely and independent analysis of fleet in-service support requirements and problems. This varies from mishap investigations to supporting the weapon system change process. These issues include, resolving competing requirements, evaluate ECP's, attending TCM, PDR, CDR meetings, supporting NATOPS changes, supporting ground and flight test and software life cycle requirements.

USE OF THE MFS FOR TRAINER SUPPORT

The concepts of the MFS software and hardware designs, and the high quality of the aerodynamic simulation databases developed has begun to transfer to the training community. The MFS has been involved in more and more programs that are outside of the its traditional role of pure test and evaluation support. The MFS has either directly updated, or delivered databases to the appropriate contractor to update existing Navy trainers. The MFS updated the F-14 training device 2F112 with an aerodynamic database, and performed and engine model upgrade on the F-14's 2F95 device. The F/A-18 high alpha departure database, and the full envelope AV-8B database have been provided to contractor agencies for installation into existing fleet assets.

The MFS hardware designs has also had impacts upon the trainer community. The MFS was tasked to produced a V-22 simulation of high enough quality that it could be used for the training of test pilots as well and T&E support. The MFS constructed a V-22 cockpit module that was an exact replica of V-22 aircraft number 3, and this device has been heavily used by the V-22 test team for both flight test support and training.

The MFS has also been involved in rapid prototyping for the trainer community. The AH-1W deployable Aircrew Procedures Trainer prototype was designed and constructed in-house by the MFS using our standard hardware and software. For the APT, however, our design team used new technology host computers that were small and rugged enough to be embedded into the cockpit module itself. The AH-1W APT rehosted the full Weapons Systems Trainer (WST) from the fleet training devices, and the entire device is constructed from off-the-shelf components. The ATP is shipped and sheltered in three Department of Defense mobile facilities, and replicates all functions of the WST except for motion cueing. The device was delivered 30 months after inception of the program. The device is pictured in the deployed configuration in Figure 5.0



AH-1W Mobile Procedures Trainer
Figure 5.0

This type of program highlights the flexibility and re-use capabilities of the MFS software and hardware standards.

Digital Flight Control System Acquisition Support Concept

DFCS Development Issues

With the introduction of the digital flight control system (DFCS) in tactical aircraft, the development and testing approach used for classical analog flight control systems were no longer sufficient and had to be modernized. In early and later DFCS programs, it was demonstrated that their development was time critical for meeting the overall aircraft schedules. The DFCS in these early programs was one of the critical aircraft systems that delayed certification for first flight. This situation existed because the DFCS is an extremely complex piece of flight critical hardware and software requiring a new approach for testing and development. These new development issues consisted of digital time delays which have a pronounced effect on aircraft flying qualities, extremely complex software development and redundancy management issues and integration requirements with other aircraft weapon systems.

DFCS Support Capacities Required

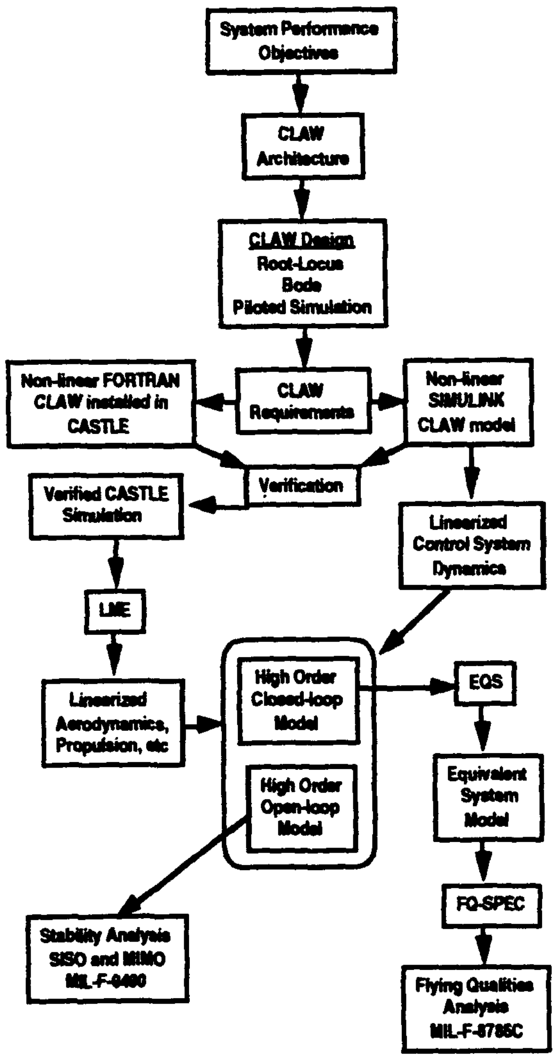
In response to the new approach needed for addressing the development issues for DFCS, the NAWCAD at Patuxent River, Maryland established a Flight Control System Support Activity including the required management structure and technical capabilities. In this capacity we execute the role as digital flight control subsystem software support activity, including life cycle planning for DFCS software. The analytical technical capabilities established included software verification and validation techniques, advanced control law design and stability analysis, redundancy management techniques and flight test methods. The hardware facilities established include manned flight simulation with cockpit and associated hardware (DDI, HUD, Display Processors, Stick, Throttle) and flight control computer test stations (FCCTS) which interface flight control computers/mission computers with the piloted simulation. A summary of our DFCS test capability is presented in figure 6.0.

Platform / Capability	F/A-18 A/B/C/D	F-14	V-22	EA-6B	F/A-18 E/F
High Fidelity Simulation	Yes	Yes	Yes	Yes	Yes
Pilot-in-the-Loop	Yes	Yes	Yes	Yes	6/96
FCC-in-the-Loop	Yes	6/94	5/94	6/94	1/95
Open Loop Testing	Yes	9/94	8/94	9/94	6/95
Closed Loop Testing	Yes	10/94	5/94	2/95	3/96

DFCS Test Capability
Figure 6.0

Integrated Control Law Design and Analysis

The Integrated control design and analysis capability is shown in figure 7.0. The approach integrates classical and modern control theory design concepts with simulation and automated analysis tools. As shown system performance objectives are established along with a control law architecture that addresses these requirements. The control law requirements are installed in non-linear form into our simulation architecture CASTLE and into our non-linear SIMULINK control law model. These control law implementations then go through a verification process. From the verified CASTLE simulation we use an automated linear model extraction tool to obtain a linearized aerodynamic and propulsion model. From the non-linear SIMULINK control law model we obtain linearized control system dynamics which are used to form a high order closed-loop model. An equivalent system analysis technique (EQS) developed in-house and is used to extract a low order model from the high order closed-loop model. This low order equivalent system model is used in conjunction with our automated flying qualities specification (FQ-SPEC) to perform a MIL-F-8785C flying qualities analysis. The CASTLE LME linearized models is used to form a high order open-loop models as the basis for conducting stability analysis to determine MIL F-9400 compliance for both SISO and MIMO characteristics.



Integrated Control Law Design and Analysis
Figure 7.0

DFCS ACQUISITION SUPPORT EXAMPLES

F-18 and F-14 examples will be used to illustrate the DFCS acquisition support. In support of the F-18 DFCS, we have established a full six degree of freedom simulation and a flight control computer test bench. This capability has been used extensively to support DFCS development and flight test. For the F-18, we have more of a tradition role in supporting the DFCS design and development. We use our capabilities to provide detailed oversight of contractor development activities through simulation studies and analysis. However, when we receive a DFCS operational flight program update we conduct an independent assessment of DFCS and OFP performance using our F-18 flight control computer test station to conduct open loop test. We also perform closed loop test using our MFS pilot in the loop simulation coupled with the F-18 FCC's.

In the case of the F-14 our role is significantly more involved with the design effort. We lead a team of government, airframe contractor and flight control computer vendor engineers to develop a DFCS for the F-14. We have led the design effort using Navy and contractor engineers to design control laws and redundancy management. In this design effort, we used the control design approach discussed earlier coupled with evaluations of the design in our MFS piloted simulation. The concept of this program is also different in that two flight control test benches were built, one for the flight control vendor and one installed in the MFS. At the MFS we are currently using this flight control bench named the Engineering Test Set (ETS) to evaluate series actuator design and the previous analog flight control computer characteristics.

TECHNOLOGY TRANSFER AND THE MFS

Long before technology transfer became a requirement for DOD laboratories, designs and ideas from MFS were moving into private industry. The interchangeable high-roll stick design used in the MFS generic cockpit module has been patented and licensed to private industry, and the video switching IOS design used in the AH-1W APT has a patent pending.

Several commercial products now on the market have their origin in the MFS laboratory. The MFS itself builds and sells multiported memories that allow the connection of a large number of dissimilar computers to a common shared memory. MFS developed 1553 bus interfaces have been transferred to industry and are on the public market, along with emulation software for the Navy standard airborne computers. The digital electronic control loaders designed and constructed for use in the MFS, is now sold in the open market.

Engineers at MFS hold several Patents for the Navy, including the unique Instructor/Operator station developed for the AH-1W program and the reconfigurable high-roll stick developed for the generic simulation cockpit.

The CASTLE software has been adopted by the Canadian Armed Forces, the Australian Armed Forces, and several university systems.

SUMMARY

In summary, we currently have an operational MFS facility and trained Navy technical staff with a full spectrum of aircraft flight fidelity simulations and cockpits including the F-18 / F-14 / V-22 / EA-6B / X-31 / T-45 / AV-8B, etc. In addition to our airframe specific cockpits we have the MRC Cockpit available for evaluation of advanced aircraft configurations and advanced aircrew/avionics/control systems. We have an integrated Navy capability to support trainer prototyping and development. Our avionics and DFCS acquisition support capabilities are in place and include mission / FCC computer and other aircraft hardware integrated into the simulation environment. The F-18 and F-14 FCC Test Stations are operational and we have advanced analytical capabilities in the areas of flight control law and stability and control and redundancy management. The MFS is integrated with ACETEF for total weapons system development. We have demonstrated our capability to participate in networking (DIS) efforts through our involvement in HYDY, WAR BREAKER and MDT2 projects.

BIOGRAPHIES

Mr. Burton is Head of the Simulation and Control Technology Department of the Strike Aircraft Test Directorate at the Naval Air Warfare Center. He is responsible for managing and conducting research/development and acquisition support programs directed towards manned and computer simulations, modern control theory, advanced system identification technology, advanced flight control system test technology, flying qualities test techniques, and the evaluation of experimental and prototype aircraft. In conjunction with these programs Mr. Burton has worked with the NATF, A-12, F/A-18, AV-8B, F-14A, F-4S, E-2C, H-60, V-22, AD-1, X-29, S-3, and F-8 OWRA aircraft. Mr. Burton received a B.S and M.E. degree from Virginia Polytechnic Institute and State University in 1966 and 1970, respectively. He graduated from the U.S. Naval Test Pilot School in 1969.

Mr. Miller is currently the section head for the tactical aircraft simulation section (SA103) of the MFS facility and the Project Leader for the development of a AH-1W Trainer for the Marine Corp. He was the lead simulation engineer on the V-22 Government Test Pilot Trainer program between 1985 and 1990. He received his B.S. degree in Aerospace Engineering from North Carolina State University of Raleigh, North Carolina in 1986.

Mr. Mills is a section head in the Computer Technology and Simulation Department of the System Engineering Test Directorate at the Naval Air Warfare Center Aircraft Division. He has been Lab Manager for the MFS facility since 1986 and is responsible for the development, integration and infrastructure of the facility. He received his B.S. degree in Electrical Engineering from West Virginia Tech in 1984.